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An energy-efficient transmission mechanism for VoIP over IEEE 802.11 WLAN

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Summary

Voice over IP (VoIP) over WLAN (VoWLAN) is an important application for public and private WLANs. However, VoWLAN systems suffer from several technical challenges such as power consumption of a WLAN station (STA) and service capacity of an access point (AP), making the commercial deployment of a large-scale VoWLAN service problematic. This study presents a cross-layer and energy-efficient mechanism for transmitting VoIP packets over IEEE 802.11 WLAN. The proposed mechanism considers the characteristics of voice packets that can tolerate certain loss, and dynamically disables the medium access control (MAC) layer acknowledgement for voice packets. In doing so, the time and energy consumed to transmit and receive voice packets for an STA can be reduced. Simulation results demonstrate that the mechanism improves the energy efficiency of a VoWLAN STA and WLAN utilization without sacrificing voice qualities. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: voice over IP (VoIP); VoIP over WLAN (VoWLAN); low power; cross-layer design; WLAN

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1. Introduction

WLANs have been widely deployed over public and private areas, and offer convenient accesses to Internet. Voice over IP (VoIP) over WLAN (VoWLAN) is considered as one of the most important applications for WLANs, and has attracted considerable interest from both academia and industry, recently [1]. However, several technical challenges inhibit VoWLAN systems such as power consumption, mobility management, WLAN utilization, and quality of services (QoSs), making a large-scale VoWLAN service difficult to deploy. Two critical issues for a VoWLAN system are the VoWLAN capacity, i.e. the number of VoIP sessions that an access point (AP) can support, and the power consumption of a VoWLAN station (STA), i.e. the standby and talk hours of a VoWLAN terminal.

IEEE 802.11 WLAN adopts carrier sense multiple access/collision avoidance (CSMA/CA) for its medium access control (MAC) [2]. The method performs inefficiently when transmitting a large amount of small MAC frames. Unfortunately, voice packets are small and are generated periodically every 10–30 ms. Several reports have already indicated that small voice packets significantly reduce the overall WLAN

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performance, thus limiting a WLAN AP to only support a small number of VoIP sessions [3,4]. To improve the WLAN utilization for transmitting voice packets, previous studies optimized WLAN parameters such as the contention window size and transmission opportunity (TXOP) for voice packets [5,6]. Wang *et al*. and Yun *et al*. presented multicast downlink transmission mechanisms that aggregate multiple downlink voice packets into one multicast packet, and transmit the packet to a group of STAs [3,7]. The overheads for inter-frame spacing (IFS) and contentions between small voice packets are eliminated, and the WLAN utilization is thus improved. However, these mechanisms require STAs to always stay awake to receive downlink multicast packets, and it does not solve the power consumption problem.

Regarding the power consumption issue for a VoWLAN system, Chen *et al*. evaluated three VoWLAN packet transmission schemes which utilize the mechanisms defined by the IEEE 802.11 power saving mode (PSM) and IEEE 802.11e automatic power saving delivery (APSD) mode [8,9]. The APSD defined in IEEE 802.11e suggests two mechanisms, i.e. the scheduled APSD (S-APSD) and unscheduled-APSD (U-APSD). The S-APSD considers the characteristic of packet voice which generates voice frames periodically. The STA that employs the S-APSD only wakes up periodically, receives and sends packets with the minimal contentions. On the other hand, the U-APSD method improves the IEEE 802.11 PSM by averting the PS-Poll procedure. An uplink voice packet can be configured as a frame to trigger a service period, which is used to transmit downlink packets. Perez-Costa *et al*. [10] further proposed a new mechanism called no data acknowledgement (NDACK) to improve the trigger frame behavior in the PSM and U-APSD mode. The conventional trigger frame requires an STA to send a trigger frame to the AP. The AP receives the trigger frame, acknowledges the trigger, and then sends the packets on the AP to the STA. If there is no packet on the AP for the STA, the AP still has to acknowledge the trigger and sends a null packet to the STA. Perez-Costa *et al*. suggested the AP to send only one NDACK frame to acknowledge the trigger and also to inform the STA when there is no packet on the AP. The NDACK mechanism only needs one handshake instead of two handshakes in the PSM and U-APSD mode when the AP does not have packets for the STA. The mechanism reduces the power consumption of an STA.

Perez-Costa *et al*. [11] also evaluated the energy efficiency of the U-APSD and further proposed the adaptive U-APSD (AU-APSD) that estimates downlink packet transmissions and determines the schedule of trigger frames. The power consumption of a WLAN STA by applying the AU-APSD can be further reduced without introducing too much packet delay. Wang *et al*. considered the characteristic of voice packet arrivals and suggested to periodically wake up STAs to receive and transmit voice packets [12]. Therefore, a time division multiple access (TDMA)-like access can be achieved for transmitting and receiving voice packets, reducing the energy consumption of an STA. Another important characteristic of voice packets that is not fully elaborated in the design of a VoWLAN transmission scheme is the need for a reliable delivery [10,13]. Reliable transmission is essential for data packets, but is not always necessary for voice packets, which could tolerate some loss. In this study, a cross-layer and energy-efficient MAC-layer transmission mechanism for voice packets is thus proposed. The mechanism dynamically disables the MAC-layer acknowledgment for each transmission attempt of a voice packet according to the current packet loss rate (PLR) and the target voice quality. By eliminating MAC-layer acknowledgments for voice packets, the time and energy consumed by sending and receiving acknowledgement frames can be reduced. Therefore, the energy efficiency of a VoWLAN STA and the WLAN utilization are both improved. To realize the proposed idea without modifying the IEEE 802.11 standard, this work adopts WLAN MAC multicasting that does not require the acknowledgement to transmit voice packets. Then, the proposed mechanism can be implemented on the existing WLAN infrastructures merely through software upgrades.

The rest of this paper is organized as follows. Section 2 describes a network architecture for a VoWLAN system and VoWLAN transmission schemes. Next, Section 3 presents the design of the proposed mechanism. Section 4 discusses the simulation results. Conclusions are finally drawn in Section 5.

2. Network Architecture and Transmission Schemes for Voice Over WLAN

Figure 1 illustrates a generic network architecture for a VoWLAN system. A VoWLAN STA is attached to WLAN *via* an AP, which is further connected to the Internet. A VoWLAN STA can then use a call setup

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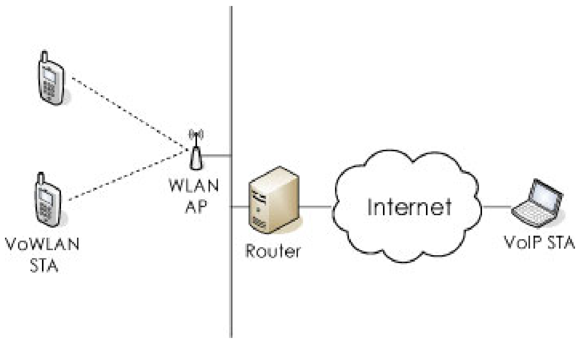

Fig. 1. A generic network architecture for a VoWLAN system.

protocol such as session initiation protocol (SIP) [14] to establish a VoIP session with a peer STA, which can be a fixed or a mobile node. In this paper, two transmission schemes that could reduce the power consumption of a VoWLAN STA are investigated. They are the PS-poll transmission scheme and the U-APSD transmission scheme.

2.1. The PS-poll Transmission Scheme

The first method, called the PS-poll transmission scheme, adopts the PSM defined in the IEEE 802.11 standard [8]. According to the PS-poll transmission scheme, an STA first notifies the WLAN AP to enter the PSM, and stays in the doze state, which consumes much less energy than the WLAN receiving state. If a VoWLAN STA has an uplink voice packet to transmit, it wakes up and sends the packet. After receiving the acknowledgement frame from the AP for the uplink voice packet, the VoWLAN STA sends a PS-poll frame to retrieve the downlink voice packet buffered on the AP. Finally, the STA receives and acknowledges the downlink voice packet. Figure 2 shows a timing diagram for uplink and downlink voice packet exchange without packet error and collision based on the PS-poll transmission scheme.

In the above figure, the active period, $T_{\text{active}}^{\text{PS-poll}}$, refers to the time period for transmitting one uplink and receiving one downlink voice packet for the PS-poll transmission scheme. Since downlink and uplink voice packets are generated periodically, say every T_i, the duty cycle of a VoWLAN STA for every T_i is given by $T_{\text{active}}^{\text{PS-poll}}/T_i$. The duty cycle is defined as the percentage of time that a VoWLAN STA is in the active period for transmitting one uplink voice packet and receiving one downlink voice packet during a T_i interval. This model assumes that the voice codec is a constant bit rate (CBR), and the codecs for uplink and downlink voice packets are symmetric. The above figure also illustrates the power consumption of a VoWLAN STA. P_{rx}, P_{tx}, and P_{dz} denote the power consumption of a VoWLAN STA during the receiving, transmitting and doze state, respectively. Clearly, the shorter length of the duty cycle that a VoWLAN transmission scheme introduces, the less energy a VoWLAN STA spends for transmitting and receiving voice packets and also the less radio resources a VoWLAN session consumes.

The power consumption of a VoWLAN STA by applying the PS-poll transmission scheme could be modeled as

$$P^{\text{PS-poll}} = \frac{T_{\text{sleep}}^{\text{PS-poll}} P_{\text{doze}} + T_{\text{active-tx}}^{\text{PS-poll}} P_{\text{tx}} + T_{\text{active-rx}}^{\text{PS-poll}} P_{\text{rx}}}{T_i} \quad (1)$$

where $T_{\text{sleep}}^{\text{PS-poll}}$, $T_{\text{active-tx}}^{\text{PS-poll}}$, and $T_{\text{active-rx}}^{\text{PS-poll}}$ are the sleep period, transmitting period, and receiving period in a

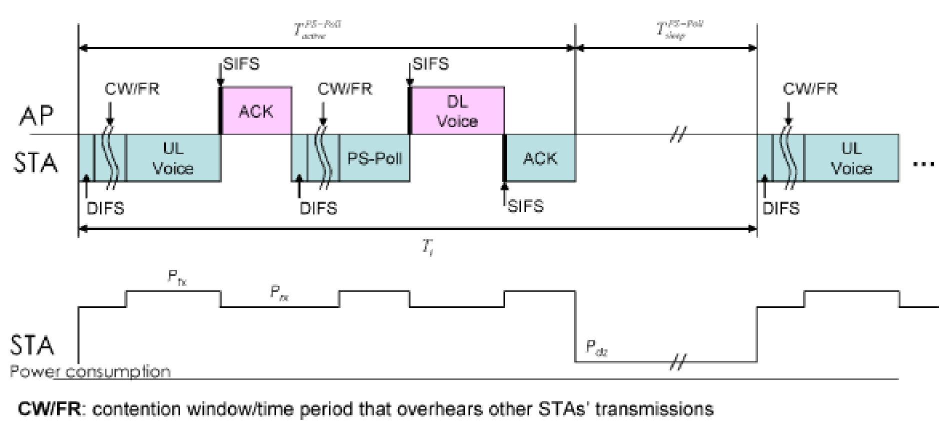

Fig. 2. PS-poll VoWLAN transmission scheme.

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T_i interval, respectively. $T^{\text{PS-poll}}_{\text{active-tx}}$ is defined as

$$T^{\text{PS-poll}}_{\text{active-tx}} = T_{\text{ul-voice}} + T_{\text{ps-poll}} + T_{\text{ack}} \quad (2)$$

where $T_{\text{ul-voice}}$, $T_{\text{ps-poll}}$, and T_{ack} represent the time periods for transmitting an uplink voice, a PS-poll frame, and an acknowledgement frame. $T^{\text{PS-poll}}_{\text{active-rx}}$ can be derived from

$$T^{\text{PS-poll}}_{\text{active-rx}} = T^{\text{PS-poll}}_{\text{active}} - T^{\text{PS-poll}}_{\text{active-tx}} \quad (3)$$

The active period, $T^{\text{PS-poll}}_{\text{active}}$, is further written as $T^{\text{PS-poll}}_{\text{active}} = T^{\text{PS-poll}}_{\text{ul}} + T^{\text{PS-poll}}_{\text{dl}}$, where $T^{\text{PS-poll}}_{\text{ul}}$ and $T^{\text{PS-poll}}_{\text{dl}}$ denote the time consumed for transmitting one uplink and one downlink voice packet, respectively. $T^{\text{PS-poll}}_{\text{ul}}$ and $T^{\text{PS-poll}}_{\text{dl}}$ could be also seen as transmission latencies for an uplink voice packet and a downlink voice packet. According to Wang's study [15], $T^{\text{PS-poll}}_{\text{ul}}$ and $T^{\text{PS-poll}}_{\text{dl}}$ are rewritten as

$$T^{\text{PS-poll}}_{\text{ul}} = T\_\text{BK} + T\_\text{FR}^{\text{PS-poll}}_{\text{ul}} + T\_\text{SU}^{\text{PS-poll}}_{\text{ul}} \quad (4)$$

and

$$T^{\text{PS-poll}}_{\text{dl}} = T\_\text{BK} + T\_\text{FR}^{\text{PS-poll}}_{\text{dl}} + T\_\text{SU}^{\text{PS-poll}}_{\text{dl}} \quad (5)$$

Above equations assume there is no packet loss due to packet collision or packet error during the transmission. T_BK denotes the time period for an STA in the WLAN MAC contention window. $T\_\text{FR}^{\text{PS-poll}}_{\text{ul}}$ and $T\_\text{FR}^{\text{PS-poll}}_{\text{dl}}$ denote the time periods for an STA that overhears other STAs' transmissions. $T\_\text{SU}^{\text{PS-poll}}_{\text{ul}}$ and $T\_\text{SU}^{\text{PS-poll}}_{\text{dl}}$ represent the time periods for an STA successfully transmitting an uplink and receiving a downlink voice packet, respectively.

Assuming that the average number of transmissions overheard by an STA before transmitting an uplink or a downlink packet successfully is given by $\overline{N^{\text{PS-poll}}_{\text{overhear}}}$, the time periods for the STA overhearing the other STAs' transmissions can be calculated as

$$T\_\text{FR}^{\text{PS-poll}}_{\text{ul}} = T\_\text{FR}^{\text{PS-poll}}_{\text{dl}} = \overline{N^{\text{PS-poll}}_{\text{overhear}}} \left(\frac{T\_\text{SU}^{\text{PS-poll}}_{\text{ul}} + T\_\text{SU}^{\text{PS-poll}}_{\text{dl}}}{2} \right) \quad (6)$$

The parameters $T\_\text{SU}^{\text{PS-poll}}_{\text{ul}}$ and $T\_\text{SU}^{\text{PS-poll}}_{\text{dl}}$ are given by

$$T\_\text{SU}^{\text{PS-poll}}_{\text{ul}} = T_{\text{difs}} + T_{\text{ul-voice}} + T_{\text{sifs}} + T_{\text{ack}} \quad (7)$$

and

$$T\_\text{SU}^{\text{PS-poll}}_{\text{dl}} = T_{\text{difs}} + T_{\text{ps-poll}} + T_{\text{sifs}} + T_{\text{dl-voice}} + T_{\text{sifs}} + T_{\text{ack}} \quad (8)$$

where $T_{\text{difs}}, T_{\text{sifs}}, T_{\text{ul-voice}}, T_{\text{dl-voice}}, T_{\text{ack}}$, and $T_{\text{ps-poll}}$ represent the time periods for the distributed coordination function (DCF) inter-frame spacing (DIFS), short inter-frame spacing (SIFS), the transmission of an uplink voice packet, a downlink voice packet, an acknowledgement frame, and a PS-poll frame, respectively.

By combing Equations (1) to (8), the power consumption of an STA ($P^{\text{PS-poll}}$), latency for transmitting an uplink packet ($T^{\text{PS-poll}}_{\text{ul}}$), and the latency for transmitting a downlink packet ($T^{\text{PS-poll}}_{\text{dl}}$) can be derived.

2.2. The U-APSD Transmission Scheme

The second method adopts the U-APSD mechanism defined in the IEEE 802.11e [8,9]. The U-APSD improves the IEEE 802.11 PSM by averting the PS-Poll procedure. An uplink voice packet can be configured as a frame to trigger a service period, which is used to transmit downlink packets. Figure 3 gives an example of an U-APSD transmitting a downlink and uplink voice packet. An STA is initially in the doze state. Once an STA has an uplink voice packet to send, it wakes up and transmits the packet. The AP responds the STA with an acknowledgment frame, starts a downlink service period, and then transmits a downlink voice packet to the STA. This approach avoids the PS-poll procedure, shortens the duty cycle, and reduces the power consumption of an STA.

The power consumption of an STA by employing the U-APSD transmission scheme is modeled as

$$P^{\text{U-APSD}} = \frac{T^{\text{U-APSD}}_{\text{sleep}} P_{\text{doze}} + T^{\text{U-APSD}}_{\text{active-tx}} P_{\text{tx}} + T^{\text{U-APSD}}_{\text{active-rx}} P_{\text{rx}}}{T_i}$$

where $T^{\text{U-APSD}}_{\text{active-tx}}$ is defined as

$$T^{\text{U-APSD}}_{\text{active-tx}} = T_{\text{ul-voice}} + T_{\text{ack}}$$

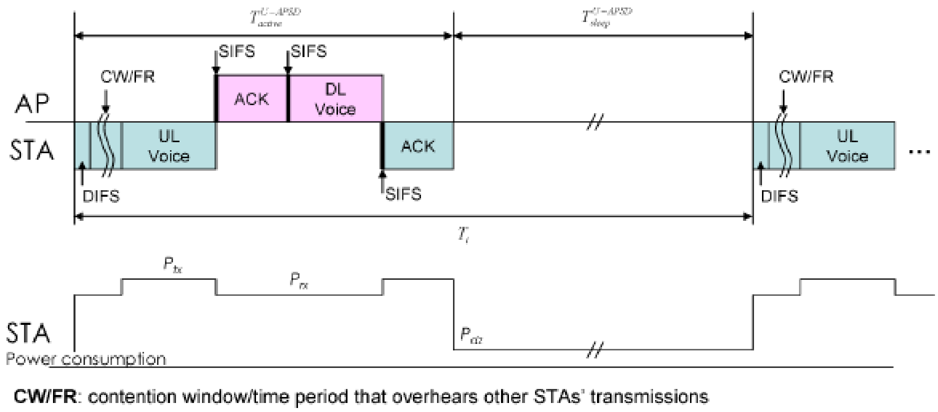

Fig. 3. U-APSD VoWLAN transmission scheme.

The active period, $T_{\text{active}}^{\text{U-APSD}}$, is derived from $T_{\text{active}}^{\text{U-APSD}} = T_{\text{ul}}^{\text{U-APSD}} + T_{\text{dl}}^{\text{U-APSD}}$. $T_{\text{ul}}^{\text{U-APSD}}$ and $T_{\text{dl}}^{\text{U-APSD}}$ are transmission latencies for an uplink voice packet and a downlink voice packet, respectively. $T_{\text{ul}}^{\text{U-APSD}}$ and $T_{\text{dl}}^{\text{U-APSD}}$ can be further defined as

$$T_{\text{ul}}^{\text{U-APSD}} = T\_\text{BK} + T\_\text{FR}_{\text{ul}}^{\text{U-APSD}} + T\_\text{SU}_{\text{ul}}^{\text{U-APSD}} \tag{9}$$

and

$$T_{\text{dl}}^{\text{U-APSD}} = T\_\text{SU}_{\text{dl}}^{\text{U-APSD}} \tag{10}$$

Since a downlink voice packet is always triggered by and immediately transmitted after an uplink voice packet, the overhearing and contention periods are not required for the downlink transmission. In the above questions, $T\_\text{FR}_{\text{ul}}^{\text{U-APSD}}$, $T\_\text{SU}_{\text{ul}}^{\text{U-APSD}}$, and $T\_\text{SU}_{\text{dl}}^{\text{U-APSD}}$ are defined as

$$T\_\text{FR}_{\text{ul}}^{\text{U-APSD}} = \overline{N_{\text{overhear}}^{\text{U-APSD}}}\left(T\_\text{SU}_{\text{ul}}^{\text{U-APSD}} + T\_\text{SU}_{\text{dl}}^{\text{U-APSD}}\right) \tag{11}$$

$$T\_\text{SU}_{\text{ul}}^{\text{U-APSD}} = T_{\text{difs}} + T_{\text{ul-voice}} + T_{\text{sifs}} + T_{\text{ack}} \tag{12}$$

and

$$T\_\text{SU}_{\text{dl}}^{\text{U-APSD}} = T_{\text{sifs}} + T_{\text{dl-voice}} + T_{\text{sifs}} + T_{\text{ack}} \tag{13}$$

By comparing Equations (4) to (8), and (9) to (13), we can derive:

$$\begin{aligned}
&T_{\text{active}}^{\text{PS-poll}} - T_{\text{active}}^{\text{U-APSD}} \\
&= \left(T_{\text{ul}}^{\text{PS-poll}} + T_{\text{dl}}^{\text{PS-poll}}\right) - \left(T_{\text{ul}}^{\text{U-APSD}} + T_{\text{dl}}^{\text{U-APSD}}\right) \\
&= T_\text{BK} + T_{\text{difs}} + T_{\text{ps-poll}} + \left(\overline{N_{\text{overhear}}^{\text{PS-poll}}} - \overline{N_{\text{overhear}}^{\text{U-APSD}}}\right) \\
&\quad \times (3T_{\text{sifs}} + 2T_{\text{ack}} + T_{\text{dl-voice}} + T_{\text{ul-voice}}) \\
&\quad + \left(2\overline{N_{\text{overhear}}^{\text{PS-poll}}} - \overline{N_{\text{overhear}}^{\text{U-APSD}}}\right) T_{\text{difs}} + \overline{N_{\text{overhear}}^{\text{PS-poll}}}\, T_{\text{PS-poll}}
\end{aligned}$$

The U-APSD scheme eliminates the PS-poll procedure comprising of one MAC contention (T_BK), one DIFS (T_{difs}), and one PS-poll frame ($T_{\text{PS-poll}}$) for an STA. The overhearing period can be further reduced if the U-APSD scheme is applied to other STAs since the active periods for all voice packet transmissions are reduced.

3. Energy-efficient Transmission Mechanism

3.1. Design of the Proposed Mechanism

The proposed transmission mechanism considers the characteristics of voice packets, and differentiates voice and non-voice packets in the WLAN MAC transmission. The initial idea is to disable the MAC-layer acknowledgement for voice packets, and to minimize the overheads for performing acknowledgements. However, to disable the MAC acknowledgement for voice packets, lost packets cannot be detected and retransmitted, and the voice quality may degrade. Therefore, the proposed mechanism is modified herein by dynamically turning

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the MAC-layer acknowledgement on and off for each transmission attempt of a voice packet, depending on the WLAN packet loss condition and the target voice quality. If packet error and loss rarely occur, then the MAC-layer acknowledgment for a voice packet is turned off, which improves the efficiency of network and energy. Conversely, while the PLR increases, the MAC-layer acknowledgement for voice packets is turned on to ensure the voice quality.

The message sequence chart of the proposed mechanism applied to the PS-poll transmission scheme is shown in Figure 4. A VoWLAN STA transmits an uplink voice packet, and then uses a PS-poll frame to retrieve a downlink voice packet on the AP. In addition to voice packets, an AP and STA may exchange non-voice packets such as SIP messages. For an uplink voice packet transmission shown in Step 4 of Figure 4, a MAC-layer transmission counter, given by $N_r^{\rm ul}$, is associated with each uplink voice packet, where $N_r^{\rm ul}$denotes the maximum number of MAC-layer transmission attempts for an uplink voice packet. Similarly, $N_r^{\rm dl}$ is associated with downlink voice packets shown in Step 6 of Figure 4. $N_r^{\rm ul}$ and $N_r^{\rm dl}$ are dynamically adjusted based on the current PLR and the target voice quality that a VoIP session sets. $N_r^{\rm ul}$ and $N_r^{\rm dl}$ are negotiated by an AP and STA, and are stored on both sides. For instance, if $N_r^{\rm ul} = 1$, an uplink voice packet is sent only once, and does not need to be acknowledged. Since $N_r^{\rm ul}$ is stored on both the STA and AP, the STA knows that the packet will not be acknowledged, so the STA can return to sleep or perform the next packet transmission without waiting for the acknowledgement frame. Therefore, the STA can save the time and energy to receive acknowledgement frames from the AP. Similarly, for a downlink packet transmission, the STA can conserve energy by not sending an acknowledgement frame for a downlink voice packet. Hence, the overheads to perform the MAC acknowledgement for voice packets are eliminated, and both the energy efficiency and WLAN utilization can be improved. If $N_r^{\rm ul} = 2$, then the uplink voice packet that is sent at the first time needs an acknowledgement from the AP. If the AP receives the packet, it acknowledges the uplink voice packet, and the transmission is complete. Otherwise, if the STA does not receive the acknowledgement from the AP, the STA detects the packet loss and resends the uplink voice packet again. Since $N_r^{\rm ul} = 2$, the resent voice packet does not need the MAC acknowledgement. The STA proceeds for the next transmission or returns to sleep after resending the voice packet. Restated, the STA sends the uplink voice packet at most $N_r^{\rm ul} - 1$ times that require the MAC-layer acknowledgement. The packet sent at the $N_r^{\rm ul}$ time needs not be acknowledged. Clearly, increasing the values of $N_r^{\rm ul}$ and $N_r^{\rm dl}$ generally improves the voice quality, but also increases the radio resource and energy consumption for a VoWLAN session. The method to determine $N_r^{\rm ul}$ and $N_r^{\rm dl}$ is discussed later in this section. Non-voice packets such as SIP messages and PS-poll frames, which are important packets and need to be reliably delivered, are transmitted with acknowledgements.

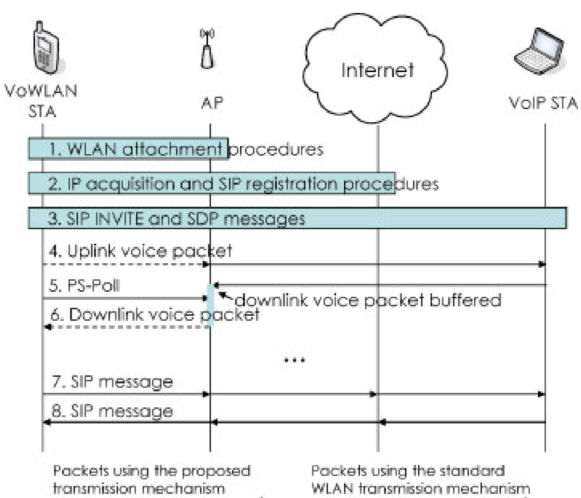

Fig. 4. The message sequence chart of the proposed mechanism applied to the PS-poll transmission scheme.

3.2. The Proposed Mechanism Applied to the PS-poll Transmission Scheme (PS-poll-M)

Figure 5 shows the timing diagram of the proposed method applied to the PS-poll transmission scheme, where both $N_r^{\rm ul} = 1$ and $N_r^{\rm dl} = 1$, i.e. voice packets are neither acknowledged nor retransmitted. Comparing Figures 2 and 5 reveals that sending packets without acknowledgement frames significantly reduces the length of a duty cycle. This is because the length of an acknowledgement frame is nearly equal to that of a small voice packet.

The power consumption of an STA by applying the proposed PS-poll-M transmission scheme is modeled as

$$P^{\rm PS-poll-M} = \frac{T_{\rm sleep}^{\rm PS-poll-M} P_{\rm doze} + T_{\rm active-tx}^{\rm PS-poll-M} P_{\rm tx} + T_{\rm active-rx}^{\rm PS-poll-M} P_{\rm rx}}{T_i}$$

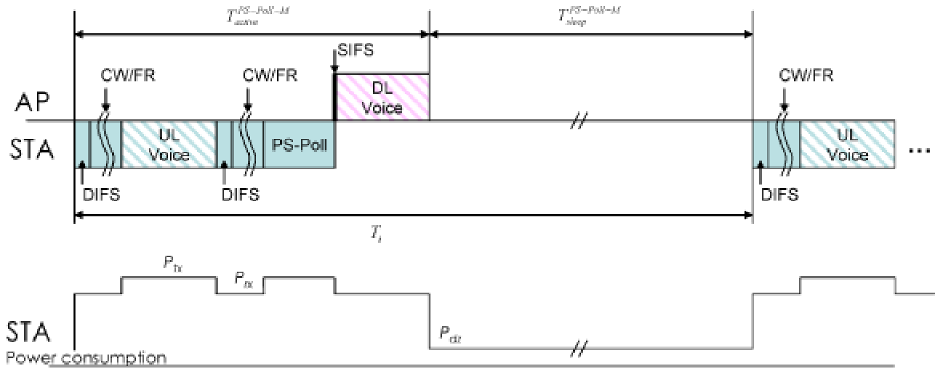

Fig. 5. Timing diagram of the proposed mechanism applied to the PS-poll transmission scheme while $N_r^{\mathrm{ul}} = 1$ and $N_r^{\mathrm{dl}} = 1$.

where $T_{\mathrm{active-tx}}^{\mathrm{PS-poll-M}}$ is defined as $T_{\mathrm{active-tx}}^{\mathrm{PS-poll-M}} = T_{\mathrm{ul-voice}} + T_{\mathrm{ps-poll}}$. The active period, $T_{\mathrm{active}}^{\mathrm{PS-poll-M}}$, is derived from $T_{\mathrm{active}}^{\mathrm{PS-poll-M}} = T_{\mathrm{ul}}^{\mathrm{PS-poll-M}} + T_{\mathrm{dl}}^{\mathrm{PS-poll-M}}$, where

$$T_{\mathrm{ul}}^{\mathrm{PS-poll-M}} = T\_\mathrm{BK}^{\mathrm{PS-poll-M}} + T\_\mathrm{FR}_{\mathrm{ul}}^{\mathrm{PS-poll-M}} + T\_\mathrm{SU}_{\mathrm{ul}}^{\mathrm{PS-poll-M}}$$

and

$$T_{\mathrm{dl}}^{\mathrm{PS-poll-M}} = T\_\mathrm{BK}^{\mathrm{PS-poll-M}} + T\_\mathrm{FR}_{\mathrm{dl}}^{\mathrm{PS-poll-M}} + T\_\mathrm{SU}_{\mathrm{dl}}^{\mathrm{PS-poll-M}}$$

In the above equations, $T\_FR_{\mathrm{ul}}^{\mathrm{PS-poll-M}}$, $T\_\mathrm{FR}_{\mathrm{dl}}^{\mathrm{PS-poll-M}}$, $T\_\mathrm{SU}_{\mathrm{ul}}^{\mathrm{PS-poll-M}}$, and $T\_\mathrm{SU}_{\mathrm{dl}}^{\mathrm{PS-poll-M}}$ are defined as

$$T\_\mathrm{FR}_{\mathrm{ul}}^{\mathrm{PS-poll-M}} = T\_\mathrm{FR}_{\mathrm{dl}}^{\mathrm{PS-poll-M}} = \overline{N_{\mathrm{overhear}}^{\mathrm{PS-poll-M}}}\left(\frac{T\_\mathrm{SU}_{\mathrm{ul}}^{\mathrm{PS-poll-M}} + T\_\mathrm{SU}_{\mathrm{dl}}^{\mathrm{PS-poll-M}}}{2}\right)$$

$$T\_\mathrm{SU}_{\mathrm{ul}}^{\mathrm{PS-poll-M}} = T_{\mathrm{difs}} + T_{\mathrm{ul-voice}}$$

and

$$T\_\mathrm{SU}_{\mathrm{dl}}^{\mathrm{PS-poll-M}} = T_{\mathrm{difs}} + T_{\mathrm{ps-poll}} + T_{\mathrm{sifs}} + T_{\mathrm{dl-voice}}$$

To compare the power consumption of an STA by applying the PS-poll scheme and the proposed PS-poll-M scheme, we assume that their WLAN MAC contention windows are equal, i.e. $T\_\mathrm{BK} = T\_\mathrm{BK}^{\mathrm{PS-poll-M}}$. The reduction of the active period by adopting the proposed mechanism can be thus derived as

$$\begin{aligned}
&T_{\mathrm{active}}^{\mathrm{PS-poll}} - T_{\mathrm{active}}^{\mathrm{PS-poll-M}} \\
&= \left(T_{\mathrm{ul}}^{\mathrm{PS-poll}} + T_{\mathrm{dl}}^{\mathrm{PS-poll}}\right) - \left(T_{\mathrm{ul}}^{\mathrm{PS-poll-M}} + T_{\mathrm{dl}}^{\mathrm{PS-poll-M}}\right) \\
&= \left(T_\mathrm{FR}_{\mathrm{ul}}^{\mathrm{PS-poll}} + T_\mathrm{FR}_{\mathrm{dl}}^{\mathrm{PS-poll}} + T_\mathrm{SU}_{\mathrm{ul}}^{\mathrm{PS-poll}} + T_\mathrm{SU}_{\mathrm{dl}}^{\mathrm{PS-poll}}\right) \\
&\quad - \left(T_\mathrm{FR}_{\mathrm{ul}}^{\mathrm{PS-poll-M}} + T_\mathrm{FR}_{\mathrm{dl}}^{\mathrm{PS-poll-M}} + T_\mathrm{SU}_{\mathrm{ul}}^{\mathrm{PS-poll-M}} + T_\mathrm{SU}_{\mathrm{dl}}^{\mathrm{PS-poll-M}}\right) \\
&= \Delta T_{\mathrm{SU}}^{\mathrm{PS-poll}} + \Delta T_{\mathrm{FR}}^{\mathrm{PS-poll}} \\
&= 2T_{\mathrm{ack}} + 2T_{\mathrm{sifs}} + \left(\overline{N_{\mathrm{overhear}}^{\mathrm{PS-poll}}} - \overline{N_{\mathrm{overhear}}^{\mathrm{PS-poll-M}}}\right) \\
&\quad \times (2T_{\mathrm{difs}} + T_{\mathrm{ul-voice}} + T_{\mathrm{dl-voice}} + T_{\mathrm{ps-poll}}) \\
&\quad + T_{\mathrm{sifs}}\left(3\overline{N_{\mathrm{overhear}}^{\mathrm{PS-poll}}} - \overline{N_{\mathrm{overhear}}^{\mathrm{PS-poll-M}}}\right) + 2T_{\mathrm{ack}}\overline{N_{\mathrm{overhear}}^{\mathrm{PS-poll}}}
\end{aligned}$$

where $\Delta T_{\mathrm{SU}}^{\mathrm{PS-poll}}$ and $\Delta T_{\mathrm{FR}}^{\mathrm{PS-poll}}$ denote the net reduction of the voice packet transmission period and overhearing period.

Then, the reduction of the energy consumption per duty cycle by adopting the proposed mechanism for the PS-poll scheme can be computed as

$$\Delta E_{\mathrm{active}}^{\mathrm{PS-poll}} = P_{\mathrm{tx}}T_{\mathrm{ack}} + P_{\mathrm{rx}}\left[\Delta T_{\mathrm{FR}}^{\mathrm{PS-poll}} + T_{\mathrm{ack}} + 2T_{\mathrm{sifs}}\right]$$

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The above equations reveal that the performance improvement of the proposed mechanism comes not only from the elimination of acknowledgement frames for downlink and uplink voice packets ($2T_{\text{ack}}$), SIFSs ($2T_{\text{sifs}}$), but also from reducing the length of the overhearing period if the proposed scheme is applied to all STAs.

3.3. The Proposed Mechanism Applied to the U-APSD Transmission Scheme (U-APSD-M)

This proposed mechanism can be also applied to the U-APSD transmission scheme, eliminating the acknowledgement frame for downlink voice packets. Notably, the uplink voice packet in the U-APSD scheme is used to trigger download packet transmissions. Therefore, the proposed design categorizes the uplink voice packets as important packets, and processes them by using the standard MAC transmission scheme to prevent the packet loss. Figure 6 gives an example of the proposed method applied to the U-APSD transmission scheme, where both $N_r^{\text{ul}} = 1$ and $N_r^{\text{dl}} = 1$.

The power consumption by applying the proposed U-APSD-M transmission scheme is modeled as

$$P^{\text{U-APSD-M}} = \frac{T_{\text{sleep}}^{\text{U-APSD-M}} P_{\text{doze}} + T_{\text{active-tx}}^{\text{U-APSD-M}} P_{\text{tx}} + T_{\text{active-rx}}^{\text{U-APSD-M}} P_{\text{rx}}}{T_i}$$

where $T_{\text{active-tx}}^{\text{U-APSD-M}} = T_{\text{ul-voice}}$.

The active period, $T_{\text{active}}^{\text{U-APSD-M}}$, is derived from $T_{\text{active}}^{\text{U-APSD-M}} = T_{\text{ul}}^{\text{U-APSD-M}} + T_{\text{dl}}^{\text{U-APSD-M}}$. $T_{\text{ul}}^{\text{U-APSD-M}}$ and $T_{\text{dl}}^{\text{U-APSD-M}}$ are

$$T_{\text{ul}}^{\text{U-APSD-M}} = T\_\text{BK} + T\_\text{FR}_{\text{ul}}^{\text{U-APSD-M}} + T\_\text{SU}_{\text{ul}}^{\text{U-APSD-M}}$$

and

$$T_{\text{dl}}^{\text{U-APSD-M}} = T\_\text{SU}_{\text{dl}}^{\text{U-APSD-M}}$$

where

$$T\_\text{FR}_{\text{ul}}^{\text{U-APSD-M}} = \overline{N_{\text{overhear}}^{\text{U-APSD-M}}} \left(T\_\text{SU}_{\text{ul}}^{\text{U-APSD-M}} + T\_\text{SU}_{\text{dl}}^{\text{U-APSD-M}} \right)$$

$$T\_\text{SU}_{\text{ul}}^{\text{PS-Poll-M}} = T_{\text{difs}} + T_{\text{ul-voice}}, \text{ and}$$

$$T\_\text{SU}_{\text{dl}}^{\text{PS-Poll-M}} = T_{\text{sifs}} + T_{\text{ack}} + T_{\text{sifs}} + T_{\text{dl-voice}}$$

The reduction of the active period per duty cycle by adopting the proposed mechanism for the U-APSD scheme can be thus derived:

$$\begin{aligned}
& T_{\text{active}}^{\text{U-APSD}} - T_{\text{active}}^{\text{U-APSD-M}} \\
&= \left(T_{\text{ul}}^{\text{U-APSD}} + T_{\text{dl}}^{\text{U-APSD}} \right) \\
&\quad - \left(T_{\text{ul}}^{\text{U-APSD-M}} + T_{\text{dl}}^{\text{U-APSD-M}} \right) \\
&= T_{\text{ack}} + T_{\text{sifs}} + \left(\overline{N_{\text{overhear}}^{\text{U-APSD}}} - \overline{N_{\text{overhear}}^{\text{U-APSD-M}}} \right) \\
&\quad \times (T_{\text{difs}} + T_{\text{ul-voice}} + T_{\text{dl-voice}}) \\
&\quad + T_{\text{sifs}} \left(3\overline{N_{\text{overhear}}^{\text{U-APSD}}} - 2\overline{N_{\text{overhear}}^{\text{U-APSD-M}}} \right) \\
&\quad + T_{\text{ack}} \left(2\overline{N_{\text{overhear}}^{\text{U-APSD}}} - \overline{N_{\text{overhear}}^{\text{U-APSD-M}}} \right)
\end{aligned}$$

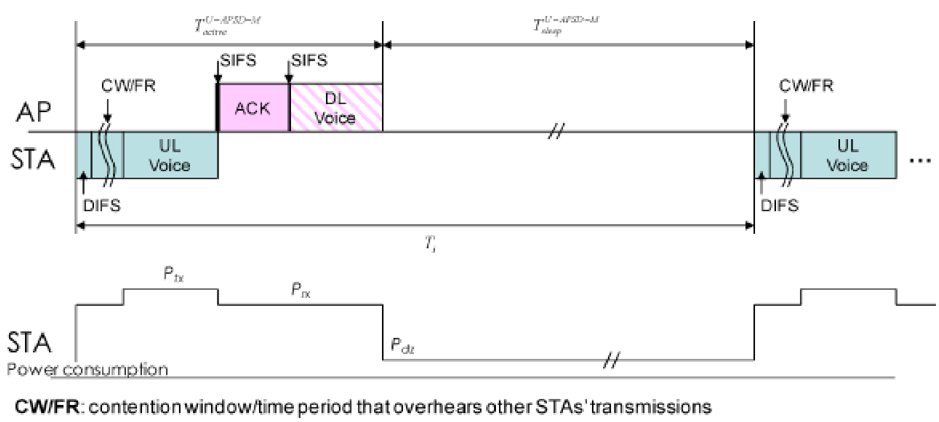

Fig. 6. Timing diagram of the proposed mechanism applied to the U-APSD transmission scheme while $N_r^{\text{ul}} = 1$ and $N_r^{\text{dl}} = 1$.

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3.4. The Maximum Number of Transmission Attempts for a Voice Packet

Disabling MAC-layer acknowledgement may introduce packet loss which degrades the voice quality. First, the contention window of each voice packet transmission does not increase when sending packets over WLANs without the MAC-layer acknowledgement. The probability of collisions rises when the number of VoWLAN session increases. Second, the WLAN channel error also introduces packet loss. To reduce packet loss and maintain voice quality, the proposed transmission mechanism defines the maximum number of transmission attempts for each uplink and downlink voice packet, say N_r^{ul} and N_r^{dl}. N_r^{ul} and N_r^{dl} are equal or larger than one, and less than the maximal retransmission counts defined in IEEE 802.11 standard. Before a VoIP session, the AP and STA first negotiate target uplink and downlink PLRs, defined as ρ^{ul} and ρ^{dl}. The measurement report for the uplink and downlink PLR are exchanged between the AP and STA every T_m. The measurement period, T_m, is a management parameter for a VoWLAN system. While the STA receives the measurement report of uplink PLR from the AP, and the uplink PLR is higher than the target loss rate ρ^{ul}, the STA increases N_r^{ul} and notifies the AP. On the other hand, if the STA detects that the uplink PLR is less than the target loss rate, the STA decreases N_r^{ul} and notifies the AP. The downlink procedures are the same. N_r^{ul} controls the uplink packet loss caused by uplink packet collision and packet error, while N_r^{dl} controls the loss rate for downlink voice packets. A VoWLAN system shall set a target voice quality in terms of the PLR and packet delay. Since the proposed mechanism always reduces the packet transmission delays by avoiding acknowledgements, the proposed mechanism adjusts N_r^{ul} and N_r^{dl} to manage the downlink and uplink packet loss and voice qualities. Typically, the target PLR is set to 1–2% for a VoWLAN application [16].

By applying the proposed mechanism, voice packets are transmitted without acknowledgement and may lose. The packet losses are caused by WLAN congestion and channel error. To model the PLR, losses due to MAC congestion and channel error shall be both taken into account. First, the packet error rate (PER), denoted as p_{e}, due to WLAN channel error can be modeled as

$$p_{\mathrm{e}} = 1 - (1 - p_{\mathrm{b}})^L$$

where p_b is the bit error rate (BER), and L is the length of a voice packet in bit. The above PER model assumes the bit error is randomly distributed to a voice packet. Regarding of the WLAN congestion loss, p_{c} is defined as the probability of a MAC collision with other STAs. p_{c} is strongly related to the contention window size of a WLAN MAC, the number of STAs contending the WLAN channel, and it could be derived from the equations presented by Reference [15]. Therefore, the probability of a packet loss, denoted as p_{loss}, could be modeled as

$$p_{\mathrm{loss}} = 1 - (1 - p_{\mathrm{e}})(1 - p_{\mathrm{c}})$$

Considering that N_r^{dl} and N_r^{ul} are configured as the maximum number of MAC-layer transmission attempts for a downlink and uplink voice packet, the PLR for the downlink voice packet and uplink voice packet can be thus modeled as

$$\mathrm{PLR}^{\mathrm{dl}} = (p_{\mathrm{loss}})^{N_r^{\mathrm{dl}}} \text{ and } \mathrm{PLR}^{\mathrm{ul}} = (p_{\mathrm{loss}})^{N_r^{\mathrm{ul}}}$$

For the proposed mechanism without acknowledgement, the PLR is $\mathrm{PLR}^{\mathrm{dl}} = \mathrm{PLR}^{\mathrm{ul}} = p_{\mathrm{loss}}$. Since the p_{loss} is much less than 1, the PLR for the conventional mechanism with acknowledgement is considerably reduced to $\mathrm{PLR}^{\mathrm{dl}} = \mathrm{PLR}^{\mathrm{ul}} = (p_{\mathrm{loss}})^{\mathrm{MAX\_RET}}$, where and MAX_RET is the maximal (re)transmission count for each MAC transmission.

3.5. Implementation Issues

To apply the proposed mechanism to the existing WLAN systems, modifications of STAs and APs are needed. These implementation issues are discussed in this section. The first issue is how to separate voice packets and non-voice packets in the MAC layer. The STAs and the APs can be enhanced to interpret some SIP and session description protocol (SDP) messages [14]. Since an STA uses SIP and SDP to establish a VoIP session with its peer, and SDP messages embed the port number information of the VoIP session. The STA and AP can thus understand the port numbers of voice packets and non-voice packets and distinguish them by the port numbers.

The second issue is adopting the WLAN MAC multicasting to transmit voice packets without acknowledgement frames. A VoWLAN STA, say STA i, is configured with two MAC addresses, one unicast address, MAC STAi, and one multicast address, MAC Mi. The WLAN MAC frame with a unicast address as the destination MAC address is used to send non-voice

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packets, and the WLAN MAC frame with a multicast address as the destination MAC address is used to send voice packets between an AP and STA. First, a VoWLAN STA associates itself with an AP using its unicast MAC address. The AP and STA then set up a shared multicast MAC address, by either implicitly producing MAC multicast address from the STA's unicast address, or explicitly exchanging a message between the STA and AP to configure a new multicast MAC address. The multicast address is only shared by the AP and the STA, and not with other STAs. Restated, each STA has its own unicast MAC address, and its own multicast address which is shared by the AP for uplink and downlink voice packet transmission. A multicast address is used as the destination MAC address of voice packets only because the MAC multicast frame does not need an acknowledgement frame from the receiver, but the multicast frame has no intent to be sent to a group of STAs. Furthermore, the additional counters N_r^{ul} and N_r^{dl} are maintained at STAs and APs. If $N_r^{\mathrm{ul}} > 1$ or $N_r^{\mathrm{dl}} > 1$, then the first $N_r^{\mathrm{ul}} - 1$ or $N_r^{\mathrm{dl}} - 1$ transmission attempts for a voice packet use the unicast MAC address, implying that the packet needs to be acknowledged. The multicast MAC address is used at the N_r^{ul} and N_r^{dl} time transmission to avoid the MAC acknowledgement. This design enables the proposed mechanism to be implemented in the existing WLAN infrastructure through only software upgrades.

Regarding of the measurement of PLRs in the proposed system, a possible solution is to implement a measurement report mechanism like IEEE 802.11k between an AP and STAs [17]. The measurement reports from both STAs and the AP containing the number of sent and received voice packet are periodically exchanged between STAs and the AP every T_m interval. The measurement reports assist STAs and the AP to adjust N_r^{ul} and N_r^{dl} to maintain voice qualities.

4. Simulation Results

To evaluate the WLAN performance and the energy consumption of a VoWLAN STA under different packet transmission schemes, a simulation program written in C is implemented. In the simulation, the VoWLAN environment comprises an AP and several VoWLAN STAs, which establish VoIP sessions and exchange voice packets with wired-line nodes in the same subnet. Table I summarizes the simulation parameters.

The length of a duty cycle, energy consumption, PLR, packet delay, and delay jitter for a VoWLAN STA by adopting the PS-poll, U-APSD with the proposed mechanism (denoted as PS-poll-M) and U-APSD with the proposed mechanism (denoted as U-APSD-M) are evaluated. The first simulation uses the IEEE 802.11b and GSM voice codec, and assumes a good WLAN channel condition, i.e. BER = 1.0e−5. Figure 7(a) shows the average duty cycle per VoWLAN STA under different numbers of concurrent VoWLAN STAs in

Table I. Simulation parameters.

	Parameters of the voice codecs		
	GSM 6.10	G.711	G.723.1
Bit rate	13.2 kbps	64 kbps	6.3 kbps
Framing interval	20 ms	20 ms	30 ms
Payload	33 bytes	160 bytes	24 bytes
	Parameters of the WLAN accesses		
	802.11b	802.11g	
		802.11 g-only	802.11b-compatable
SIFS/DIFS/Slot time	10/50/20 μs	10/28/9 μs	10/50/20 μs
PHY preamble + header (short /long)	192/96 μs	20/9 μs	192/96 μs
PS-Poll/ACK	80/56 μs	27/19 μs	80/56 μs
CWmin/CWmax	32/1024	16/1024	32/1024
Data rates	11 Mbps	54 Mbps	54 Mbps
Parameters of the power consumption of a WLAN interface (ORiNOCO PC Gold, IEEE 802.11b) [18]			
$P_{\mathrm{tx}}/P_{\mathrm{rx}}$		1400/950 mW	
P_{doze}		60 mW	

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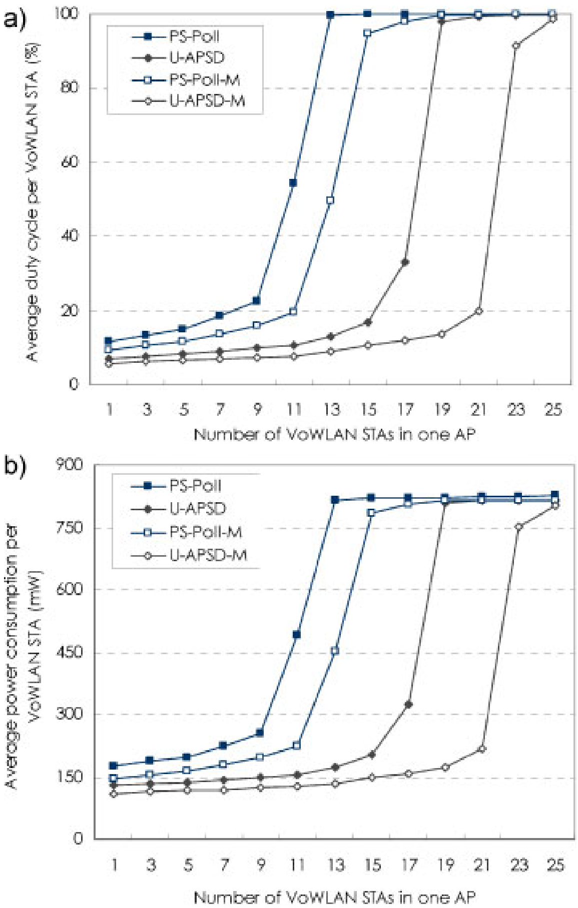

Fig. 7. (a) Average duty cycle and (b) energy consumption for a VoWLAN STA.

an AP. The y-axis of Figure 7(a) shows the length of a duty cycle which indicates the percentage of time that a VoWLAN STA must stay awake to transmit one uplink and one downlink voice packet every voice framing interval. A larger percentage of a duty cycle per voice framing interval implies that more energy is consumed for a VoWLAN STA. Figure 7(a) indicates increasing the number of concurrent VoWLAN STAs in an AP also increases the average duty cycle per VoWLAN STA, because a VoWLAN STA needs to spend more time contending the WLAN channel when more concurrent VoWLAN STAs are served by an AP. The figure illustrates that while the number of VoWLAN STAs in an AP is one, the PS-Poll and U-APSD transmission schemes with the proposed mechanism decrease by about 10% length of a duty cycle than the transmission schemes without the proposed mechanism. This performance improvement is gained only by eliminating acknowledgement frames and some SIFSs. The performance improvement by applying the proposed mechanism grows as the number of concurrent VoWLAN STAs in an AP increases. This is because that a VoWLAN STA has to wait for other VoWLAN STAs' transmissions while the AP is serving many VoWLAN STAs. The proposed mechanism reduces the transmission time of voice packets, and hence, significantly reduces the average length of an overhearing period while the WLAN load becomes heavy. For instance, the average active period per VoWLAN STA for the PS-poll and PS-poll-M scheme when nine concurrent VoWLAN STAs are served are 4.48 and 3.16 ms, respectively. The proposed mechanism reduces the duty cycle by about 29%. The average active period for the U-APSD and U-APSD-M schemes are 1.96 and 1.48 ms, respectively, indicating a reduction of about 24% when adopting the proposed mechanism for the case that nine VoWLAN STAs are served by an AP. The simulation results reveal that the proposed method removes the acknowledgement frames for voice packets, thus shortening each duty cycle, which also reduces the WLAN channel waiting time while a VoWLAN STA tries to transmit a voice packet.

To evaluate the improvement of energy consumption, the energy consumption of a VoWLAN STA using different transmission schemes was investigated. ORiNOCO PC Gold Card is used for this simulation [18]. Figure 7(b) shows the corresponding energy consumption of Figure 7(a). The proposed mechanism reduced the average energy consumption of PS-poll and U-APSD by about 23 and 17%, respectively, while an AP is serving nine concurrent VoWLAN STAs.

Voice packets for which acknowledgement frames are not sent might be lost due to packet error or collision, degrading the voice quality. Therefore, the proposed mechanism dynamically adjusts the maximum number of transmission attempts, i.e. N_r^{ul} and N_r^{dl}, for each voice packet based on the target PLRs. In the simulations, the maximum permissible PLR is set to 2%. Figure 8 shows the average loss rates for uplink and downlink voice packets by applying different transmission schemes. The simulation results show that although the PLRs of the PS-poll-M and U-APSD-M scheme were slightly higher than those of the PS-poll and U-APSD scheme, the PLRs for the proposed transmission mechanism are still less than 1%.

The packet delays of different transmission schemes are then investigated. Figure 9 shows the average delay for uplink and downlink voice packets. The figure indicates that the voice packets encounter longer delays as the number of VoWLAN STAs served by

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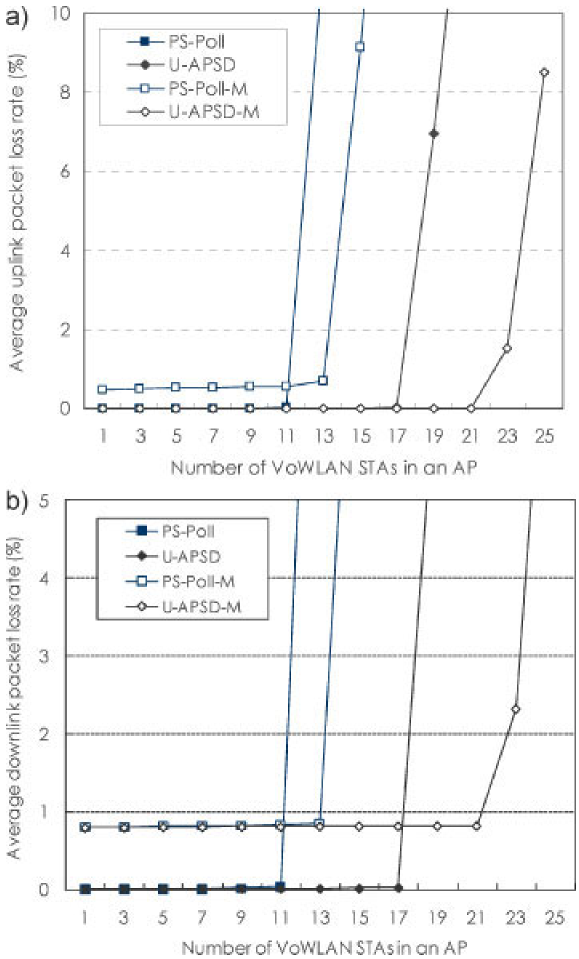

Fig. 8. Average loss rates for (a) uplink and (b) downlink voice packets.

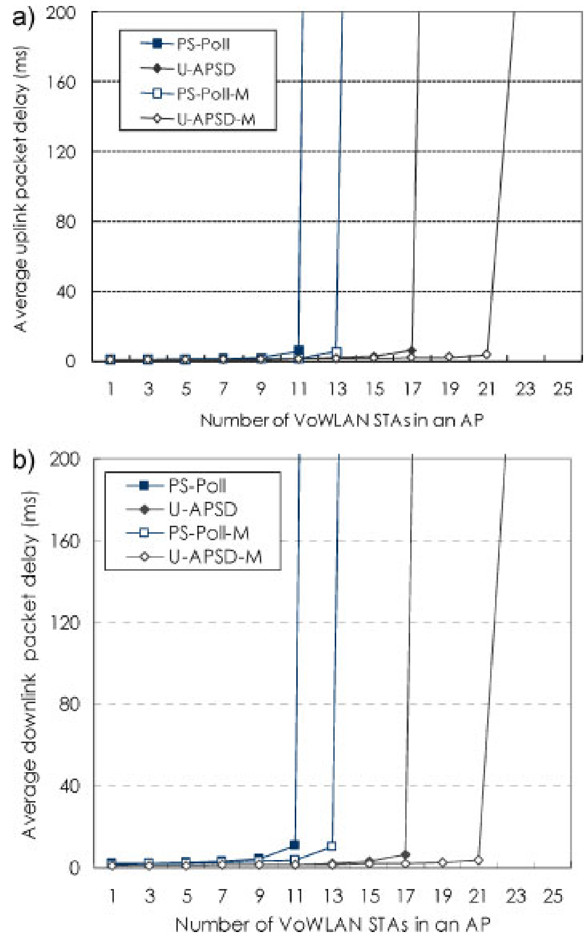

Fig. 9. Average delay for (a) uplink and (b) downlink voice packets.

an AP increases. This is because that increasing the WLAN load causes more packets to be queued on the AP, increasing the packet delay. Since the proposed mechanism reduces the length of a duty cycle, it increases the maximal number of VoWLAN STAs that can be supported by a WLAN. Simulation results indicate that the PS-poll-M scheme can support two more VoWLAN STAs than the PS-poll scheme under a 50 ms delay and 2% loss rate constraints of voice packets. The U-APSD-M scheme is found to support four more VoWLAN STAs than the U-APSD scheme. Simulation results depicted in Figures 8 and 9 reveal that the proposed mechanism improves the WLAN utilizations of the PS-poll and U-APSD transmission schemes by about 18 and 24% in terms of the number of supported VoIP sessions and can provide similar voice qualities.

Figure 10 illustrates the cumulative distribution function (CDF) of inter-packet arrival time while the number of VoWLAN STAs in an AP is 11. As we can see from the figure, the proposed mechanism does not introduce extra variation of inter-packet arrival time comparing with the conventional approaches. According to the simulation results, the PS-poll, PS-poll-M, U-APSD, and U-APSD-M scheme achieve 20.00, 20.13, 20.00, 20.08 ms mean inter-packet arrival time and 6, 3, 6, and 3 standard deviations, respectively. This is because the proposed mechanism eliminates the acknowledgement frames. A packet without an acknowledgement may lose but the arrival time of the packet is a little bit earlier than the packet with acknowledgement. Also, the number of retransmission per voice packet by applying the proposed mechanism is less than that by employing the conventional mechanisms. To dynamically enable or disable acknowledgements for voice packet transmissions, the packet delay may become fluctuated. In order to evaluate the delay

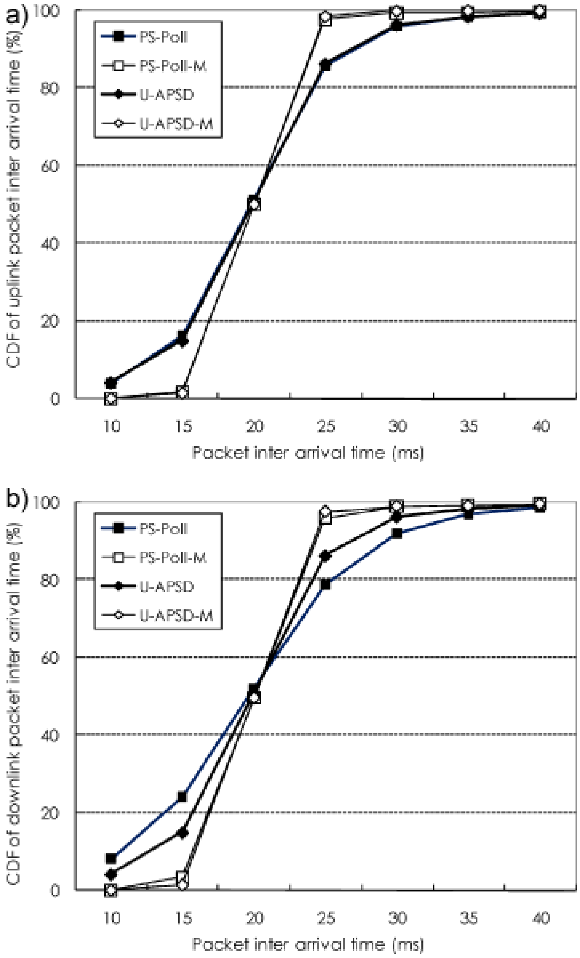

Fig. 10. CDF of inter-packet arrival time for (a) uplink and (b) downlink voice packets.

jitters cased by this design, the above simulation is slightly modified. The new simulation randomly picks up the conventional PS-poll transmission scheme with acknowledgement or the proposed PS-poll-M mechanism without acknowledgement, and uses the transmission scheme to transmit a voice packet. In other words, the transmission scheme for every voice packet may be different. Then, the simulation can evaluate the delay and delay jitters for transmitting voice packets while the MAC acknowledgement is dynamically disabled and enabled. Simulation results show that the average downlink and uplink packet delay by applying the conventional PS-poll transmission scheme are 5.68 and 4.2 ms. The standard deviations of the downlink and uplink packet delay, which can be seen as the delay jitter, are 5.04 and 4.2. On the other hand, the average downlink and uplink packet delay by applying the proposed PS-poll-M transmission scheme are 1.8 and 1.3 ms. The standard deviations are 2.4 and 2.1. By dynamically enabling and disabling the MAC acknowledgement, the average downlink and uplink packet delay become 3.8 and 2.8 ms. The standard deviations become 4.2 and 3.4. The simulation results reveal that by applying different transmission schemes or dynamically enabling and disabling the MAC acknowledgement, the jitters could be all accommodated by the same jitter buffer size. The jitter buffer of a VoIP application is normally 1–3 voice frames, and it could accommodate about 20–60 ms delay and delay jitters.

Table II summarizes the average duty cycles of a VoWLAN STA for different voice codecs while an AP serves one VoWLAN STA. The simulation is based on IEEE 802.11b and the long preamble. Comparing GSM 6.10 and G.711 which have the same framing interval, the simulation results reveal that the improvement by employing the proposed mechanism increases while the voice codecs have small

Table II. Summary of average duty cycle of a VoWLAN STA under different voice codecs while the AP serves one VoWLAN STA.

Voice codec	PS-poll (%)	PS-Poll-M (%)	Percentage of improvement (%)
GSM 6.10	11.6	9.2	21
G.711	12.7	10.8	15
G.723.1	7.7	6.1	20.8

Table III. Summary of average duty cycle of a VoWLAN STA under different WLAN technologies while the AP serves one VoWLAN STA.

WLAN standard		PS-poll (%)	PS-poll-M (%)	Percentage of improvement (%)
802.11b (short preamble)		8.7	7.2	17.2
802.11b (long preamble)		11.6	9.2	21
802.11g	11b-compatible (short preamble)	6.5	5.6	13.8
	11b-compatible (long preamble)	9.4	8.0	14.9
	11g-only (short preamble)	2	1.79	10.5
	11g-only (long preamble)	2.33	2.06	11.6

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payloads. This is because our proposed mechanism eliminates the acknowledgement frames and IFSs which introduce serious overheads in transmitting small voice packets rather than large voice packets. We further compare the improvement by employing the proposed mechanism for GSM 6.10 with a 33-byte payload and G.723.1 with a 24-byte payload, and we find that the improvement by applying the proposed mechanism for G.723.1 is similar to that for GSM 6.10. This is because G.723.1 has a 30-ms framing interval meaning that the average number of packets per second for G.723.1 is less than GSM 6.10. In other words, the numbers of acknowledgement frames and IFSs per second for G.723.1 are less than these for GSM 6.10. The improvement by applying the proposed mechanism becomes less significant for voice codecs introducing less number of packets per second, i.e. less numbers of acknowledgement frames and IFSs.

We further evaluate the performance by applying the proposed mechanisms in different WLAN standards and configurations. Table III summarizes the results. The simulation is based on GSM 6.10 codec and an AP serves one VoWLAN STA. Obviously, the improvements by applying the proposed mechanism for long preambles are better than short preambles. Long preambles introduce more header overheads for packet transmissions than short preambles, and the proposed mechanism can reduce the overheads and improve the energy efficiency. The simulation results also show that the improvement by applying the proposed mechanism under low speed WLAN such as IEEE 802.11b is more significant than high speed WLAN such as IEEE 802.11g. This is because the overheads introduced by acknowledgment frames and IFSs have been reduced by the IEEE 802.11g standard. The improvement by eliminating these overheads is significant in IEEE 802.11b and IEEE 802.11g/IEEE 802.11b-compatable environments.

Finally, the performance improvement of the proposed mechanism under mixed video and data traffic load is evaluated. In the first simulation, the video traffic is introduced as the background traffic. The simulation uses the IEEE 802.11b, GSM voice codec, and BER = 10e−5 as the parameters. There are three bi-directional video conference sessions between three STAs and the AP. Each video conference generates 64 Kbps H.263 video from a STA to the AP and from the AP to the STA. In other word, each video conference session occupies 128 Kbps bandwidth of the WLAN. Then, different numbers of VoWLAN sessions are further added. In the simulation, the video

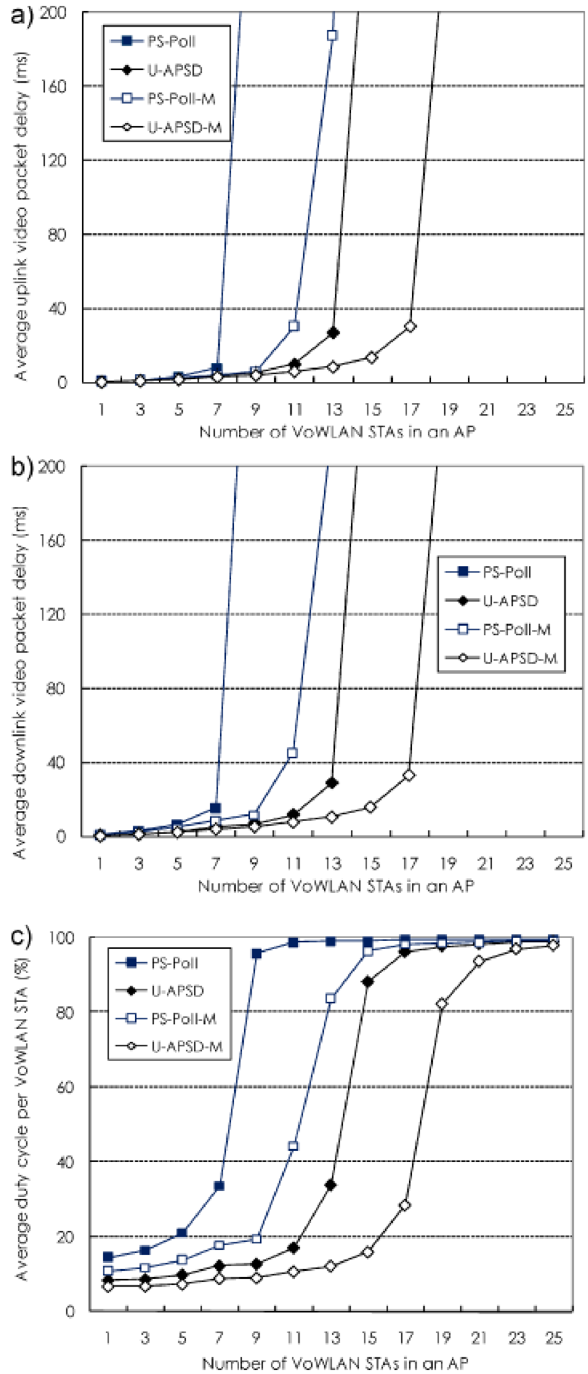

Fig. 11. Average (a) uplink and (b) downlink packet delay for video sessions and (c) the duty cycle for voice sessions.

and voice packets share the same transmission priority. Figure 11(a) and (b) depict the average downlink and uplink packet delay for video conference sessions. It can be seen from the figures that the delay for the video packets is not influenced too much by

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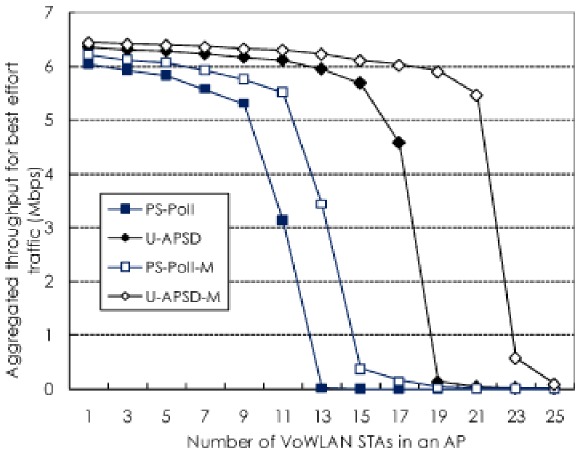

Fig. 12. Aggregated throughput for best effort traffic.

applying our proposed mechanism under the same number of supported VoWLAN sessions. Figure 11(c) illustrates the average duty cycle for VoIP sessions. The simulation results show that our proposed mechanism achieves better performance than the conventional approaches under CBR background traffic. Also, the video sessions are not influenced too much.

In the second simulation, the best effort data are introduced as the background traffic. The best effort packets are downlink only from the AP to STAs. The priority of best effort data is lower than the voice packets in this simulation. Figure 12 shows the aggregated downlink throughout for the best effort traffic. It can be seen from the figure that the throughput for the best effort data are further improved by employing our proposed mechanism. This is because our proposed mechanism saves the radio resources by eliminating acknowledgement frames and some IFSs for voice packets. These resources can be used to transmit more best effort packets.

5. Conclusions

This study presents a cross-layer and energy-efficient transmission mechanism for a VoWLAN system. The mechanism dynamically disables the MAC acknowledgement for each transmission of a voice packet according to the current PLR and the target voice quality, thus reducing the time and the energy consumed by a VoWLAN STA in transmitting and receiving voice packets. Simulation results indicate that the proposed mechanism significantly reduces the energy consumption of a VoWLAN STA, and improves the WLAN utilization for transmitting voice packets without sacrificing voice qualities. Furthermore, WLAN multicasting is used to transmit voice packets without the MAC acknowledgement, thus enabling the proposed mechanism to be implemented on the existing WLAN infrastructure by software upgrades.

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